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Invasion threats of *Acacia mearnsii* on the growth performance of *Pinus patula* in Sao Hill Forest plantation

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**INVASION THREATS OF *Acacia mearnsii* ON THE GROWTH
PERFORMANCE OF *Pinus patula* IN SAO HILL FOREST
PLANTATION**

Nanyika Kingazi

**A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of
Master's in Life Sciences at the Nelson Mandela African Institution of Science and
Technology**

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ABSTRACT

This study aimed at determining the extent (distribution, density and structure) of *Acacia mearnsii* invasion as well as assessing its influence on the performance of *Pinus patula* by comparing, stem density, basal area and standing volume between invaded and non- invaded areas in Sao Hill Forest Plantation (SHFP). A systematic random samplings technique was used to select sample plantation blocks and plots allocation. The results showed that there was a significant difference between the mean population density per hectare of *A. mearnsii* in the margins and inside plantation blocks ($F\text{-value} = 61.4$, $df=278$, $p = 0.0000$), with greater mean population density being in the margin than inside the plantation blocks. Also, a significant difference between the size class group (seedlings, saplings, poles and adults) was found in the mean population density of *A. mernsii* ($F\text{-value} = 26.28$, $df = 278$, $p = 0.0000$), with the greater mean population density being in seedlings followed by a sapling, sub-adults, and adults. Moreover, there was a significant difference between invaded and non-invaded areas across different age classes of *P. patula* in all variables measured with greater density, basal area and volume being in non-invaded than invaded areas. The study found that, an invasive tree *A. mearnsii* has a negative impact (reduction) on the survival and growth of *P. patula* in all age classes sampled. This study suggests that forest management strategies should incorporate invasive plant control given that the performance of desirable tree species can be influenced by plant invasions. This may include clearing of the *A. mearnsii* stands before they mature to flowering and thus, limiting seed production.

Keywords: *Acacia mearnsii*, *Pinus patula*, distribution, density, structure, competition, performance, invaded and non-invaded.

DECLARATION

I, Nanyika Kingazi do hereby declare to the senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is entirely my original work and that it has neither submitted nor being submitted for degree award in any other institution.

Name and Signature of candidate

Date

Nanyika Kingazi

The above declaration is confirmed

Name and Signature of Supervisor 1

Date

Dr. Linus Munishi

Name and Signature of Supervisor 2

Date



Dr John Richard

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CERTIFICATION

The undersigned certify that they have read and hereby recommend the dissertation entitled “Invasion threats of *Acacia mearnsii* on the growth performance of *Pinus Patula* in Sao Hill Forest Plantation” as a fulfillment of the requirement for the degree Master of Life Sciences at the Nelson Mandela African Institution of Science and Technology.

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Dr John Richard

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DEDICATION

I dedicate this Dissertation to God Almighty my creator, my strong pillar, my source of inspiration, wisdom, knowledge, and understanding. He has been the source of my strength throughout this research and on His wings only have I soared. I also dedicate this dissertation to my beloved Husband; Kiezera Alfred who has encouraged me all the way and whose support has made sure that I give it all it takes to finish this work. To my beloved children Moreen and Moses who tolerated my absence during this study. Further dedications go to my parents Mr. and Mrs. Emmanuel Kingazi for their prayers, encouragement, and support during this work. Thank you. My love for you all can never be quantified. God bless you.

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LIST OF ABBREVIATIONS AND SYMBOLS

CDC	Colonial Development Corporation
DBH	Diameter at Breast Height
FAO	Food and Agriculture Organization
FBD	Forest and Beekeeping Division
SHFP	Sao Hill Forest Plantation
TAFORI	Tanzania Forestry Research Institute
TANWAT	Tanganyika Wattle
TFS	Tanzania Forest Services

CHAPTER ONE

INTRODUCTION

1.1 Background of the problem

Widespread forest degradation, loss, and exploitation is a global problem with severe consequences and long-lasting effects (Bonan, 2008; Miles & Kapos, 2008; Hosonuma *et al.*, 2012) on biodiversity (Maxwell, Fuller, Brooks & Watson, 2016) and climate (Lawrence & Vandecar, 2015). It further exacerbates species loss and livelihoods of those who rely on the resources provided by these ecosystems (Harley, 2011). Globally, forests are undergoing major changes driven by factors related to climate, land-use and natural disturbances which lead to lose much of their integrity (Bebi *et al.*, 2017). Several initiatives have been adopted to rescue forest including protection and sustainable management of the existing forests as well as restoration of degraded forests (Food and Agriculture Organization [FAO], 1999). In some countries such as Tanzania, apart from above-mentioned initiatives, the establishment of planted forests is also used to rescue natural forest as it provides alternative industrial wood materials, fuelwood and non-wood forest products (FAO, 2003; Pirard *et al.*, 2016; Forest Beekeeping Division [FBD], 2017). Mbwambo, Bakengesa and Nshubemuki (2011) reported that, apart from wood materials, planted forests play a greater role in the provision of ecosystem services such as carbon sequestration, nutrient cycle, recreational value, and soil erosion control. Sao Hill Forest Plantation (SHFP) is one of the plantations established for that purpose (Ngaga, 2011).

Establishment of forest plantations in Tanzania started way back in the 1890s during German colonial rule with different exotic tree species including pines, acacias, teak, and cypress (Kilawe, Maliondo, Jonas & Amanzi, 2013). Large scale forest plantation started in early 1950 in various parts of the country (FBD, 2017). Currently, the total forest plantation area in Tanzania is 554 500 hectares under both public and private ownership regimes with *P. patula* being the main species planted (Malimbwi, Mugasha & Mauya, 2016). Exotic tree species are preferred due to their fast-growing nature, quick adaptability to local conditions, simple silviculture as well as excellent national and international market (Kilawe *et al.*, 2013). They also provide a substitute for wood materials that would have come from natural forests

(FAO, 2005) as well as the provision of ecosystem services such as carbon sequestration, nutrient cycling and recreational value (Mbwambo *et al.*, 2011).

Despite its importance, forest plantations in Tanzania are facing many challenges including frequent forest fire, pest, and diseases (Mbwambo *et al.*, 2011). Apart from those challenges, invasive wood weed species are also becoming a threat in managing forest plantations as they invade plantation and compete with the planted species for resources (Iddi *et al.*, 1998; Nagabona & Chitiki, 2016). *Lantana camara* in the Buhindi forest plantation (Iddi *et al.*, 1998) and *A. mearnsii* in SHFP (Nagabona & Chitiki, 2016) are among of the heavily invaded wood weed invasive species being reported. This study aimed at providing detailed information on the extent of *A. mearnsii* invasion in SHFP and how it influences the performance of *P. patula* the mainly planted species in this plantation. This study will contribute into developing a strategy for controlling the invasion by providing baseline information about the problem.

1.2 Statement of the problem

Sao Hill Forest Plantation, which is the largest forest plantation in Tanzania, was established in 1939 for the production of pulpwood and timber (Kangalawe, 2018). The plantation is currently supplying about 85 % of wood materials consumed by wood industries in Tanzania (Ngaga, 2011). Much of this plantation is dominated by Pines mainly *P. patula* (Ngaga, 2011). The productivity in SHFP is facing challenges such as frequent forest fires, pests, and disease (Mbwambo *et al.*, 2011). In recent years, the invasion by *A. mearnsii* has added to the problems and has raised serious concern on the forest productivity and plantation management costs (Nagabona & Chitiki, 2016). Most of the compartments (blocks) in the plantation have been invaded by the *A. mearnsii* as several patches of this species can be seen inside planted trees especially in *P. patula*. Several measures have been taken to control the spread and growth of this *A. mearnsii* in the plantation, mainly by uprooting them. The method has not worked as the *A. mearnsii* is still spreading and growing in the plantation thus posing every year cost of removing it from the forest. The average estimated cost of uprooting is 132 667 138.7 Tanzania Shillings as the cost data were taken for two years of 2013/2014 and 2014/2015. Also, there is a growing concern over the increase of *A. mearnsii* in SHFP, as a result, *P. patula* is being suppressed and sometimes killed and replaced by this *A. mearnsii* which further reduces stocking of the plantation trees at the end of the rotation (Nagabona & Chitiki, 2016).

Until now limited studies have been conducted or published concerning *A. mearnsii* invasion and its effects in forest plantations. Therefore, following the invasion of *A. mearnsii* in SHFP, this study aimed at assessing the invasion of *A. mearnsii* in SHFP in term of distribution and density as well as how it influences the performance of *P. patula* by comparing survival, stem density, DBH distribution and standing volume between invaded and non- invaded areas. The study will provide basic information that will help forest managers, tree growers and government on how to address the problem. It will also help to understand the impact of *A. mearnsii* on *P. patula* and the need for preventing and controlling once infested any *P. patula* plantation to ensure its maximum productivity.

1.3 Rationale of the study

In order to realize the sustainable production and efficient turnover from the SHFP, extent of *A. mearnsii* invasion and its competition effects to the planted species especially *P. patula* need to be studied so that appropriate measures can be set based on the evidence from the reseach.

1.4 Objectives

1.4.1 General objective

To determine the status and influence of *A. mearnsii* invasion on the growth performance of *P. patula* in Sao Hill Forest Plantation, Southern Tanzania.

1.4.2 Specific objectives

- (i) To map the current areas invaded by *A. mearnsii* in Sao hill forest plantation, southern Tanzania.
- (ii) To assess density and structure of *A. mearnsii* in Sao hill forest plantation, Southern Tanzania.
- (iii) To assess the influence of *A. mearnsii* on the performance of *P. patula* in Sao hill forest plantation, Southern Tanzania.

1.5 Research questions

- (i) What is the distribution status of *A. mearnsii* in the Sao hill forest plantation, Southern Tanzania?

- (ii) What is the density and structure of *A. mearnsii* in Sao hill forest plantation, Southern Tanzania?
- (iii) What is the influence of *A. mearnsii* on the performance of *Pinus patula* in Sao hill forest plantation, Southern Tanzania?

1.6 Significant of the study

This study provides the current information regarding the invasion status of *A. mearnsii* and its influence on the performance of *P. patula*. It provides baseline information and a comprehensive understanding of the implications of the invasion to the management and sustainability of SHFP. This information will be incorporated into management actions towards dealing with the problem and its consequences on ecosystem services provisioning including timber production in the plantation and surrounding areas.

1.7 Delineation of the study

This study focused on the assessing the extent of *A. mearnsii* invasion (distribution, density and structure) and its effects on the growth performance of *P. patula* in SHFP. Thus, this study did not consider the effect of *A. mearnsii* on other planted tree species or native species/ environment.

CHAPTER TWO

LITERATURE REVIEW

2.1 Biological invasion

Biological invasions have increased rapidly all over the world in recent decades (Van Wilgen *et al.*, 2011). It is one of the significant threats to biodiversity, economy, and environment by causing vast damage to valuable ecosystems and their services (Simberloff, 2013). Biological invasions associated with non-native trees have increased in many parts of the world (Richardson *et al.*, 2014). These invasions cause a detrimental impact on the environment, society, and economic activities and are the key drivers of global change (Shackleton, Maitre, Pasiecznik & Richardson, 2014). Invasive tree species are known to reduce native wood species density, growth and richness (Shackleton, Wilgen & Richardson, 2015; Van Der Waal, 2009). Likewise, such invasive trees negatively affect ecosystem services such as water supply, reduces grazing land, affects soil quality as well as reducing crop production (Shackleton *et al.*, 2014; Reda & Tewelde, 2017). Australian acacias (genus *Acacia*) are a useful model group for understanding tree invasions (Richardson *et al.*, 2011). *Acacia mearnsii* is among the Australian tree species that were introduced to new locations worldwide (e.g. Tanzania) for different purposes such as wood and tannin extraction (Richardson, Roux & Wilson, 2015; Richardson *et al.*, 2011), and later became an invasive alien species (Rejm & Richardson, 2013).

2.2 Biology and ecology of *Acacia mearnsii*

Acacia mearnsii is commonly known as Black wattle (Richard, 2016). It is a fast-growing leguminous small to a large, evergreen, single-stemmed or multi-branched tree, 6-25 m high, with a straight or crooked trunk, growing to 50 cm in diameter (Dunlop, Resende & Beck, 2005). *Acacia mearnsii* starts to flower when reaches about 2 years but an adequate amount of seed (up to 20 000 seeds/m²) starts to be produced from 5 to 6 years. It produces a large amount and long-lived seed, which could remain viable for 50-100 years (Sandoval, 2015). *Acacia mearnsii* is a light-demanding species with rapid early stem growth, it can grow up to 3 m per year (Wiersum, 1991). The altitudinal, temperature and rainfall range of *A. mearnsii* is 300-2440 m.a.s.l, 9-20 °C and 1500-2050 mm respectively. The soil conducive for *A. mearnsii* is deep, well drained, light textured, moist soil, well aerated, neutral acid and loam soil (Orwa,

Mutua, Kindt & Jamnadass, 2009).

Acacia mearnsii can tolerate a wide range of sites in various climates from temperate and subtropical lowlands to tropical highlands. The natural occurrence of *A. mearnsii* falls mostly in the warm sub-humid zone, extending in places to the warm humid zone. At the highest altitudes, it occurs in the cool subhumid and humid zone (Sandoval, 2015). In its native range, *A. mearnsii* forms part of the understorey in eucalypt woodland (Weber, 2003). Outside its native range, *A. mearnsii* is an invader along river corridors and in coastal scrub, forest, and grassland (Weber, 2003). *Acacia mearnsii* is often found in the closed forest as a result of having previously established in gaps when the forest was more open, as it is not able to establish in closed forests (Geldenhuys, Roux & Cooper, 1986).



Figure 1: *Acacia mearnsii* trees

2.3 Distribution of *Acacia mearnsii*

The species is native to South-Eastern Australia from 35–44°S latitude (New South Wales, Queensland, Victoria, and Tasmania). It has been introduced throughout the tropics and

subtropics. Large commercial plantations are found in southern and eastern Africa (Kenya, South Africa, and Zimbabwe), Brazil and India. In other areas such as Europe and America *A. mearnsii* plants are smaller or introductions have not been successful (Dunlop *et al.*, 2005). It is widespread in indigenous South African forests occurring both along forest edges, in gaps of various sizes and inside the closed forest (Geldenhuis *et al.*, 1986) and it can invade pasture land (PIER, 2007). In Tanzania, *A. mearnsii* was probably firstly introduced in Southern Tanzania in the 1940s by Colonial Development Corporation (CDC) and planted around Njombe District (Nickol, 2015). It was mainly planted in plantations that have been managed by the Tanganyika Wattle Company (TANWAT) for tannin extraction. It was also disseminated and planted by the community as field margin trees and for commercial purposes (Nickol, 2015).

2.4 Uses of *Acacia mearnsii*

Due to its nitrogen-fixing potential, *A. mearnsii* is used in intercropping with maize, cassava, tobacco, and various vegetables. It also yields bark extractives (tannin) used in the manufacture of leather goods and adhesives (Nigro, 2008). The leaves of *A. mearnsii* have high protein content (15%) used as fodder. *Acacia mearnsii* is a moderately dense wood, splits easily, burns well and makes excellent fuelwood and charcoal. It also produces wood that is used for construction poles, tool handles, cabinetwork, joinery, flooring, construction timber, matchwood, hardboard, and paper pulp. It is a useful species for erosion control, soil improvement, shade, shelter, and ornament (Chan *et al.*, 2015).

2.5 Invasiveness of *Acacia mearnsii*

Apart from being a very useful species, *A. mearnsii* is regarded as a highly invasive species. The invasiveness of this species is due to its ability to produce large numbers of long-lived seeds with a variety of potential dispersal mechanisms including water, mammals and possibly birds, rapid growth, allelopathic effect and the development of a dense crown that shades other vegetation (Dunlop *et al.*, 2005). *Acacia mearnsii* is listed as one of the World's 100 Worst Invaders (Global Invasive Species Database [GISD], 2019). It has also been listed as a category 2 invader in South Africa, a noxious environmental weed in the Global Compendium of Weeds, and a noxious weed in the USA (Sandoval, 2015). It is one of the most important plant invaders of the fynbos, South Africa (Wells, 1991) and also invades pine plantations (Geldenhuis *et al.*,

1986). It is also known to be invasive in California, USA, Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda, Zimbabwe, Jamaica, Brazil, New Zealand. It causes several environmental problems and is hard to control because of its ability to form root suckers (Sandoval, 2015).

2.6 Effect of *Acacia mearnsii* on ecosystem

Acacia mearnsii have a variety of negative impact to the environment such as altering stream functionality and reducing species diversity of aquatic biota (Van Der Waal, 2009; Railoun, 2018), affecting soil and litter carbon stock (Oelofse & Jakob, 2015), altering soil physiochemical properties and change microbial function and structure as well as competing and replace other vegetation (Souza-alonso, 2017). The study conducted in Chome Nature Reserve, Tanzania about the coverage, the effect and estimated control cost of *A. mearnsii* showed that, until 2016, species covered about 210 ha, which is equivalent to 1.5% of the total reserve area, it affects the regeneration of native species such as *Ocotea usambarensis* and reduces water yield of the forest. The estimated cost of control this species is about 164.64 million per year (Richard, 2016). Nagabona and Chitiki (2016) reported that *A. mearnsii* has invaded SHFP which cause planted species particularly pine species to be outcompeted and replaced by *A. mearnsii* as a result it reduces stock at the end of rotation age.

2.7 Control measures of *Acacia mearnsii*

According to Sandoval (2015), *A. mearnsii* can be controlled in several ways depending on the size of the tree. Seedlings and saplings trees younger than 3 years can be controlled using a cultural method (fire), a chemical method such as glyphosate and biological methods such as seed feeders and mycoherbicides. The mechanical method is used for sprouts and mature trees.

2.8 Ecology, distribution and uses of *Pinus patula*

Pinus patula is an evergreen, monoecious, medium-sized tree up to 30(–50) m tall, bole branchless for up to 15 m, up to 120 (–150) cm in diameter, usually straight and cylindrical; bark surface grey to dark brown, broken into longitudinal (Nigro, 2008). *Pinus patula* is native to Mexico and it was introduced into many African countries, and it has become the most important pine in East and southern Africa (Nigro, 2008). It is also grown in Australia, New Zealand, Asia, and South America. *Pinus patula* is grown at 1000–3300 m altitude, in areas

with a mean annual temperature of 9–23°C, a mean maximum temperature of the warmest month of 15–29°C, a mean minimum temperature of the coldest month of 6–14°C, an average annual rainfall of (700–) 1000–2200 mm, and a dry season of up to 4 months. It grows best at higher altitudes: above 1000 m.a.s.l at 18–30° latitude, and above 2000 m.a.s.l near the equator; several provenances tolerate severe frost (Nigro, 2008). The common soil suitable for *P. patula* includes acidity and good moisture supply. In the east African highlands, it performs well in young fertile volcanic soils and on mature leached infertile soils derived from basement complex on other sites in East Africa and South Africa (Orwa *et al.*, 2009)

Pinus patula grows very fast. Under favorable conditions, it may attain a height of 15 m after 8 years and 35 m after 30 years (Nigro, 2008). During the first year after planting out 2–3 weeding operations are required. *Pinus patula* self-prunes poorly, so trees are pruned when 4–6 years old to a height up to 2.5 m, to reduce fire hazard and improve access ('low pruning'). In pulpwood plantations, no further pruning is done, although pruning up to a height of 6 m height has been recommended to reduce the risk of fire. For the production of sawn timber, dead, as well as living branches up to a height of 7(–12) m, are removed to produce knot-free timber ('high pruning') (Nigro, 2008). Thinning depends on initial spacing, site quality, and end product. For the production of sawlogs, the final aim is a stand of about 400 trees/ha with a bole diameter of about 45 cm, which implies rotations of 25–35 years. The total yield (including thinnings) under favorable conditions maybe 630–700 m³/ha (Nigro, 2008; Malimbwi, 2016).

Pinus patula has a variety of uses, it is an important source of wood, pulpwood, and resin (Orwa *et al.*, 2009). Wood from young trees is mainly used to manufacture boxes, and that of older trees for light construction, light flooring, joinery, ceilings, paneling, shingles, furniture, cabinetwork, fence posts, poles, food containers, pallets, mine props, veneer, and plywood. It is also suitable for hardboard, particleboard, and wood-wool. *Pinus patula* is also excellent for fuelwood and the production of charcoal (Nigro, 2008). *Pinus patula* is the main species planted in forest plantations in Tanzania (Malimbwi *et al.*, 2016; Ngaga, 2011)



Figure 2: “Right” *Pinus patula* with no *Acacia mearnsii* invasion, “Left” *Pinus patula* block with *Acacia mearnsii* invasion

CHAPTER THREE

MATERIAL AND METHODS

3.1 Study site

This study was conducted in Sao Hill Forest Plantation (SHFP) which is located in the Southern Highlands of Tanzania, Iringa region, Mufindi District at (8°18'S to 8°33'S and 35°6'E to 35°20'E) with the altitude which ranges from 1700 m to 2000 m.a.s.l (Mugasha *et al.*, 2016). The area is a rolling plateau with low hills and wide flat-bottomed valleys. The rainfall pattern is unimodal with a single rain season from November through May and a dry season during the rest of the year. The area receives between 750 and 2010 mm of rainfall annually (Ngaga, 2011). Temperatures are fairly cool, reaching close to a freezing point between June and August. The mean monthly minimum and maximum temperatures are 10°C and 20°C respectively (Mugasha *et al.*, 2016).

The soils are relatively homogeneous and are mainly dystric nitosols in association with Orthic acrisols (Ngegba, 1998). These are sandy clay loam soils with a relatively uniform physical structure in an undisturbed state, color ranging from very dark brown to yellow-orange, drained and moderate acidic (Ngaga, 2011).

Sao Hill forest plantation was established in 1939 with the main objective of supplying raw material to wood industries (pulpwood and timber), protecting water catchment areas, preventing soil erosion, improving local climate, and acting as a buffer between local people and the natural forest (Ngaga, 2011). The plantation covers a total area of 135 903 ha. The total planted area is 57 570 ha, out of which 54 070 ha are planted with pines particularly *P. patula* and 3500 ha with cypress and eucalyptus species. The remained area composes natural forests and river valleys managed as water catchment areas, extension areas and residential areas. This makes the SHFP be the largest plantation in Tanzania (Tanzania Forest Services [TFS], 2020).

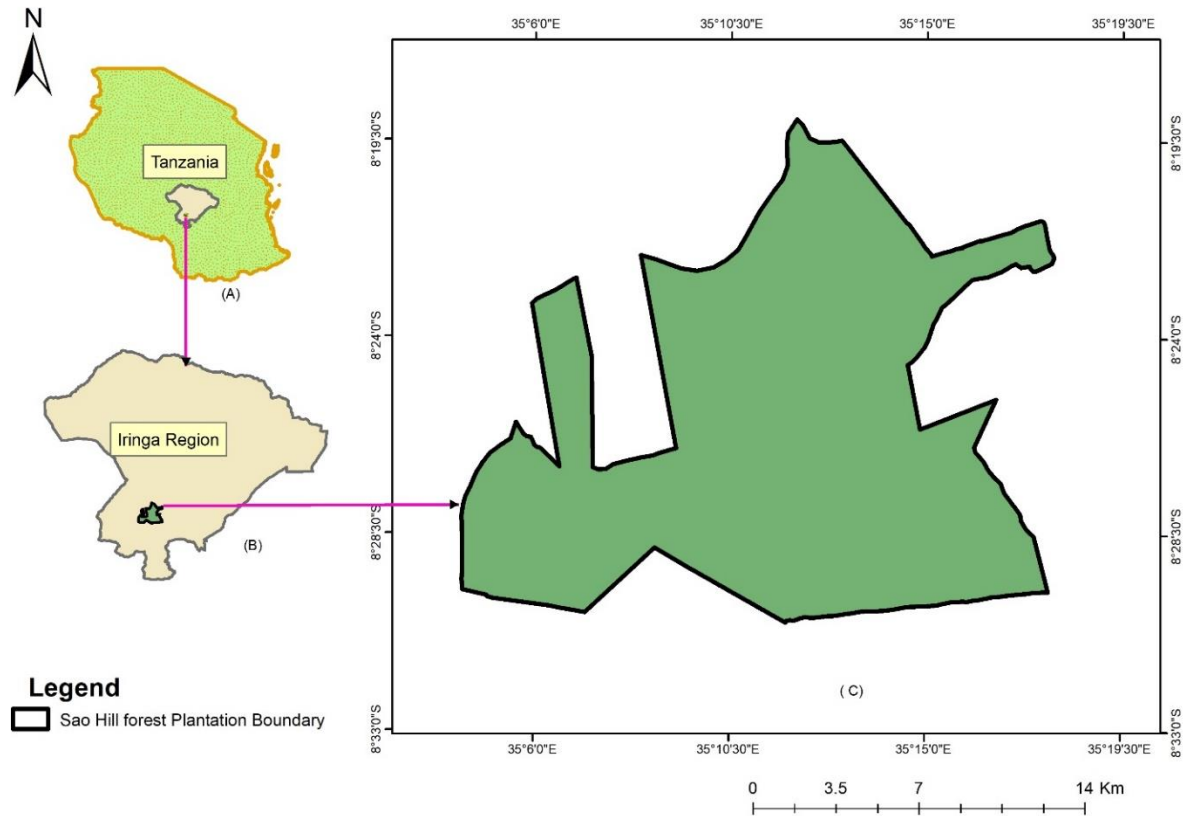


Figure 3: Map of the study area; Sao Hill Forest Plantation

3.2 Sampling design and data collection

A reconnaissance survey was conducted between December 2018 and January 2019 using vehicles along the forest road and transect walk for about 50 m in off-road areas to determine sampling strategy. Data collection was conducted from February to March 2019. For *A. mearnsii* and *P. patula* measurement, seven invaded *P. patula* blocks were systematically randomly selected. Block as per this study refers to the management unit (section of forest with homogeneous growth conditions and tree species). Before selection, blocks were grouped into the following age class 1-5 years, 6-10 years, 11-15 years, 16-20 years, 21-25 years, 26-30 years and 31-35 years (Vesa *et al.*, 2010). In each category, blocks with the following ages; 4, 8, 11, 17, 25, 28 and 33 were randomly selected to represent age classes. The choice of the plantation block was based on the dominance of *A. mearnsii* with at least one side which is completely not invaded that was used as a control (for comparison).

3.2.1 Distribution of *Acacia mearnsii*

Acacia mearnsii distribution data were collected by recording coordinates to each encountered patch along the road and transect during reconnaissance survey. Coordinates for distribution were also recorded at the center of each established plot along transect during *Acacia mearnsii* density data collection. Moreover, distribution data were recorded up to 2 km from the SHFP boundary into the natural vegetation, which was considered as a buffer area. Coordinates were recorded by using Global Position System (GPS) Garmin 64S a handheld device and then projected into a datum WGS 84 and Zone 36S.

3.2.2 Density and structure of *Acacia mearnsii*

In each sample block, 2 transects of 20 m apart and 100 m length were laid out lengthwise from the beginning to the end of the plantation block. 1 transect was laid along the margin of the plantation block and another transect was laid inside a block (60 m from the margin). Five concentric nested circular plots Vries (1996) were systematically allocated along each transect line. The distance between plots was 25 m to ensure plots variation (Ward & Sutherland, 2006). Concentric plots were used for data collection as according to Vesa *et al.* (2010) who reported that the use of concentric plots in forest inventory increases the accuracy of the measurement and sampling intensity of large trees, and simultaneously saves time. Also, it ensures that small trees are measured in small plots and large trees are measured in large plots. The total number of plots was 35 along the blocks margin and 35 inside blocks.

All *A. mearnsii* plants were counted based on their respective groups such as seedlings, saplings, poles, and adult trees and their amount determined per plot. The plots within a 2 m radius were used to assess the density of all seedlings and within a 5 m radius of the plot all saplings were counted. Poles and adults were counted in 10 m and 15 m radius respectively. Saplings were the young trees with a diameter size class of 2 cm to 5 cm. The tree seedlings were those with diameter size class < 2 cm as recommended by Luoga, Witkowski & Balkwill, (2004) and Lejju, (2004). Poles were those of ≥ 6 cm but < 20 cm DBH and all trees with DBH ≥ 20 cm were considered as adult trees (Edward, Munishi & Hulme, 2009).

Table 1: Summary of study design for density and structure of *Acacia mearnsii* data collection

Block number	Number of transects		Number of plots	
	Margin/edge	Inside block	Margin/edge	Inside block
1	1	1	5	5
2	1	1	5	5
3	1	1	5	5
4	1	1	5	5
5	1	1	5	5
6	1	1	5	5
7	1	1	5	5
Total	7	7	35	35

3.2.3 Survival, density and growth performance of *Pinus patula*

In each sample block, 2 transects with 20 m apart and 100 m length were laid out lengthwise from the beginning to the end of the block. one transect was laid along the invaded part of the block and another transect was laid along the non invaded part (100 m from the invaded part). About five concentric nested circular plots with a 10 m radius (Vries, 1996) were systematically allocated along each transect line. The distance between plots was 25 m to ensure plot variation (Ward & Sutherland, 2006). The total number of plots was 35 in the invaded area and 35 in the non-invaded area.

In both invaded and non-invaded plots, *P. patula* data were collected by counting the number of stems and measure its growth parameters; total tree height and diameter at breast height (DBH). The diameter was measured in all trees in the plot while height was measured in only to a subset of trees in the plot (large, medium and small diameter size) and the allometric equation was used to estimate the height of the remained trees (Vesa *et al.*, 2010). In invaded plots, *A. mearnsii* stems were also counted and measured its DBH.

Table 2: Summary of the study design for survival, density and growth performance of *Pinus patula* data collection

Block Number	Age Class	Age of <i>Pinus patula</i> block	Number of Transects		Number of Plots	
			Invaded area	Non-Invaded area	Invaded area	Non-Invaded area
1	1-5	4	1	1	5	5
2	6-10	8	1	1	5	5
3	11-15	11	1	1	5	5
4	16-20	17	1	1	5	5
5	21-25	25	1	1	5	5
6	26-30	28	1	1	5	5
7	31-35	33	1	1	5	5
Total			7	7	35	35

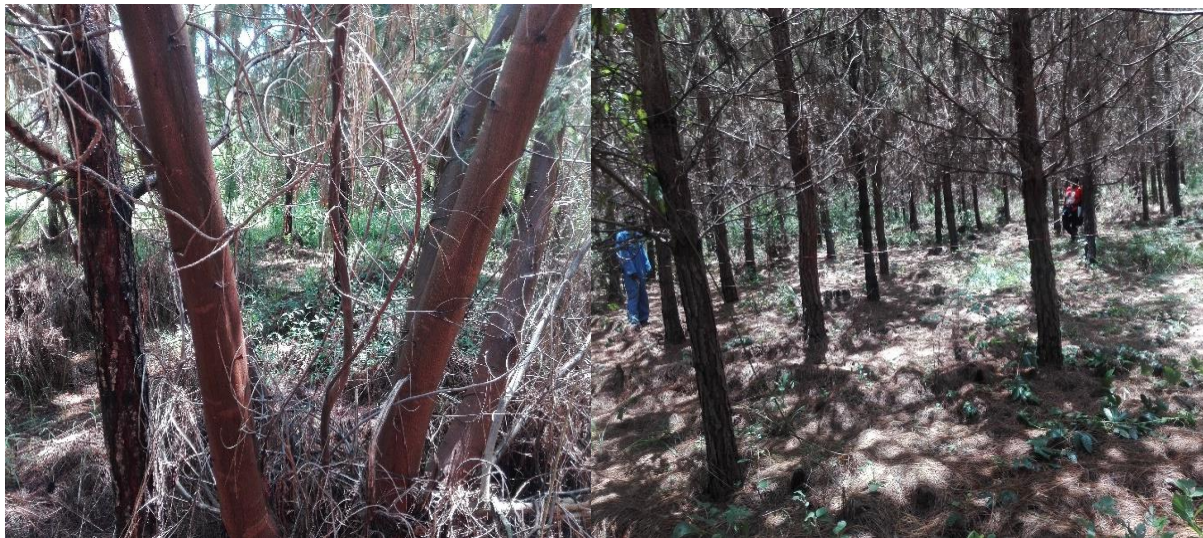


Figure 4: Block of 8 years *Pinus patula* invaded with *Acacia mearnsii* (left) vs non- invaded (right)

3.3 Data analysis

3.3.1 Distribution of *Acacia mearnsii* in SHFP

Distribution of *A. mearnsii* in the entire SHFP area was analyzed using Arc GIS (Arc Map version 10.6) to produce the distribution and density map. This was done by using the GPS coordinates recorded during the field survey, the abundance of all counts in the survey plots

and the patterns of this in the entire study area. Patterns of change across the SHFP were analyzed by comparing the ranges in the density of population categories, intersecting the digitized map of SHFP with coordinates from the survey plots and transects. Values of *A. mearnsii* population density per hectare were then run in the kernel density tool in the arc map version 10.6. The Kernel tool calculated the spread and spatial distribution of the *A. mearnsii* across the landscape to create a continuous surface with a search radius of one square kilometer. Kernel tool calculated density units based on the linear unit of the projection of the output spatial reference. The SHFP is bordered by village/communal land with varied complex landscapes in terms of uses, and the map included a 2 km buffer to reflect the role of borderlines on the invasion by *A. mearnsii* in the plantation blocks.

3.3.2 Density and structure of *Acacia mearnsii*

Population density estimates of *A. mearnsii* in the study area was calculated as a summation of all counts in the plot divide by plot area. The population structure of the *A. mearnsii* was examined by calculating the percentage contribution of each age category in the total population. After calculation, the results were subjected to normality test to determine if they were normally distributed to qualify for analysis of variance. After confirming that data were normally distributed, one-way analysis of variance (One way-ANOVA) was used to assess the difference between the margins and inside block plantation density as well as the variation between different age categories (Edward *et al.*, 2009).

3.3.3 Survival, density and growth performance of *Pinus patula*

Pinus patula survival was calculated by simply dividing the number of stems counted in a plot with the number of stems required in a plot when planting space is 3 m × 3 m multiplying by 100% (Chamshama & Nshubemuki, 2011; FBD, 2017). The relationship between survival and the number of *A. mearnsii* was obtained by Pearson's correlation analysis after the Normality test. Computation of volume of *P. patula* started by estimating height (m) of trees that were not measured in the field using equation

$$Height = 1.3 + (dbh^2 / 13.63898 + 0.026482 \times dbh^2) \quad (1)$$

where, dbh is the diameter at breast height (Malimbwi, Mugasha & Mauya, 2016). Then height and DBH data were used to estimate the standing volume of individual *P. patula* using equation

$$Volume = \exp (-9.04925 + 1.14781 \times \ln(height) + 1.5496 \times \ln(dbh)) \quad (2)$$

Volume per hectare was calculated by summing up individual tree volume dividing by plot area in ha (Malimbwi *et al.*, 2016) and presented into a bar graph. After calculations summaries of results for density per ha and volume in meter cubic per ha (m³ ha⁻¹) of *P. patula* in both invaded and non-invaded plots were tested for normality and subjected into paired sample T-test in R software version 3.5.2 for the statistically significant test.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Result

4.1.1 Distribution, density and structure of *Acacia mearnsii* in SHFP

Acacia mearnsii showed variation in density between different areas in the SHFP (Figure 5). The highest *A. mearnsii* density was recorded in North – East and South – East of the SHFP where density reaches a total of 10 000 plants per ha.

The mean population size (mean \pm SE) of *A. mearnsii* per hectare was 1603 (\pm 77) seedlings, 1483 (\pm 21) saplings, 726 (\pm 14) poles and 111 (\pm 23) adults along the plantation block margins (Fig. 6 and 7). Inside the plantation blocks, population size was 132 (\pm 8), 99 (\pm 7), 70 (\pm 5) and 19 (\pm 5) *A. mearnsii* per hectare for seedlings, saplings, poles, and adult trees, respectively (Fig. 6 and 7). Mean population size of *A. mearnsii* was significantly larger along the margins than inside the plantation blocks (F -value = 61.4, df 278 P = 0.0000, n = 280). Mean population density between age groups was significantly different (F -value = 26.28, df 278 p = 0.0000 n = 280), decreasing from *A. mearnsii* seedlings to saplings to poles to adults.

In the margin number of *A. mearnsii* juvenile trees (seedlings and saplings) exceeded the number of mature trees (poles and adult tree) by 57.2% with 78.6% and 21.4% respectively. Generally, coverage of seedlings (41%) was higher than other age group followed by sapling (37.6%), poles (18.4%) and adult trees (3%)

Inside blocks number of *A. mearnsii* seedlings was also high compared to other age groups as they cover about 41% of the total mean population density per hectare followed by saplings 30.8%, poles 21.8% and adult tree 5.9%.

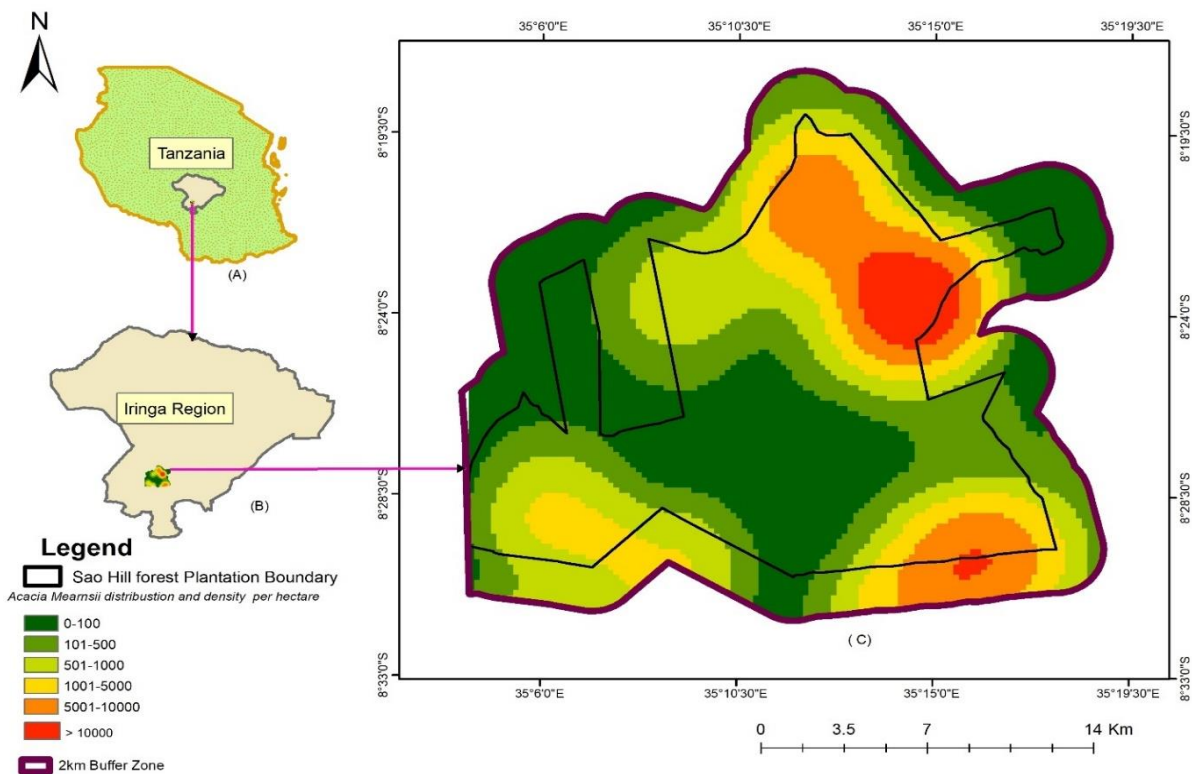


Figure 5: Distribution and population density per hectare of *Acacia mearnsii* in different areas of Sao Hill Forest Plantation

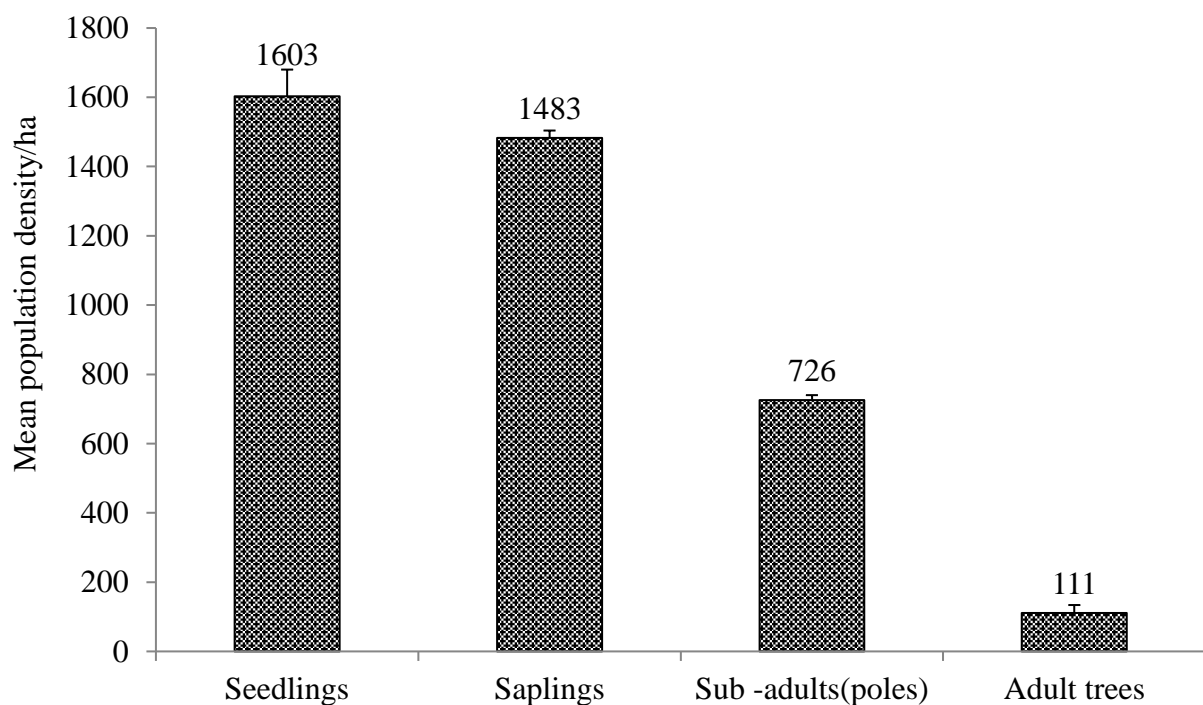


Figure 6: Mean population density (SE±) of *Acacia mearnsii* per hectare along blocks margins

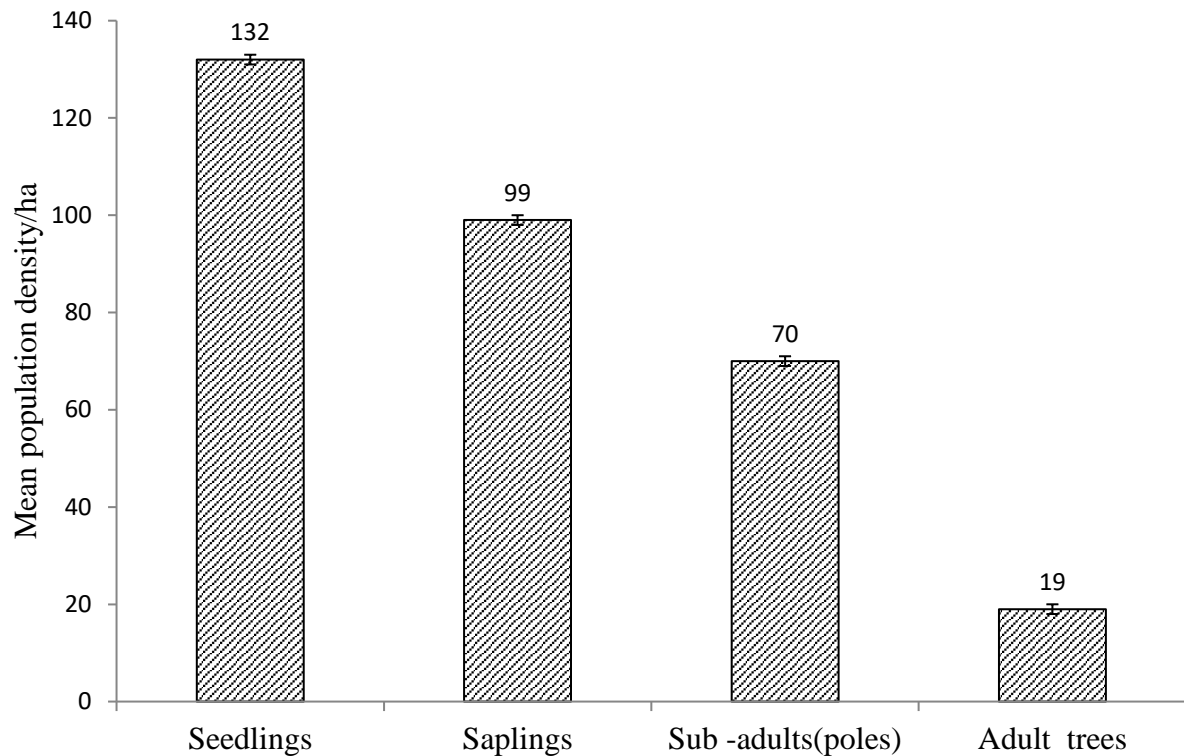


Figure 7: Mean population density (SE±) of *Acacia mearnsii* per hectare inside plantation blocks

Moreover, High recruitment of *A. mearnsii* was observed in the blocks with matured *A. mearnsii* trees which in most cases were found in the sampled blocks with matured *P. patula*. Also, a large population density of seedlings was observed in blocks with young pine trees between 0-5years.

4.1.2 Relationship between number of *Acacia mearnsii* and survival of *Pinus patula*

The correlation relationship between number *A. mearnsii* and *P. patula* survival in invaded areas is shown in (Fig. 7). There was a significant negative correlation between *P. patula* survival and an increase in the number of *A. mearnsii*, such that *P. patula* survival was decreasing as the number of *A. mearnsii* increased ($r = -0.36$, $df = 34$, $p\text{-value} = 0.033$).

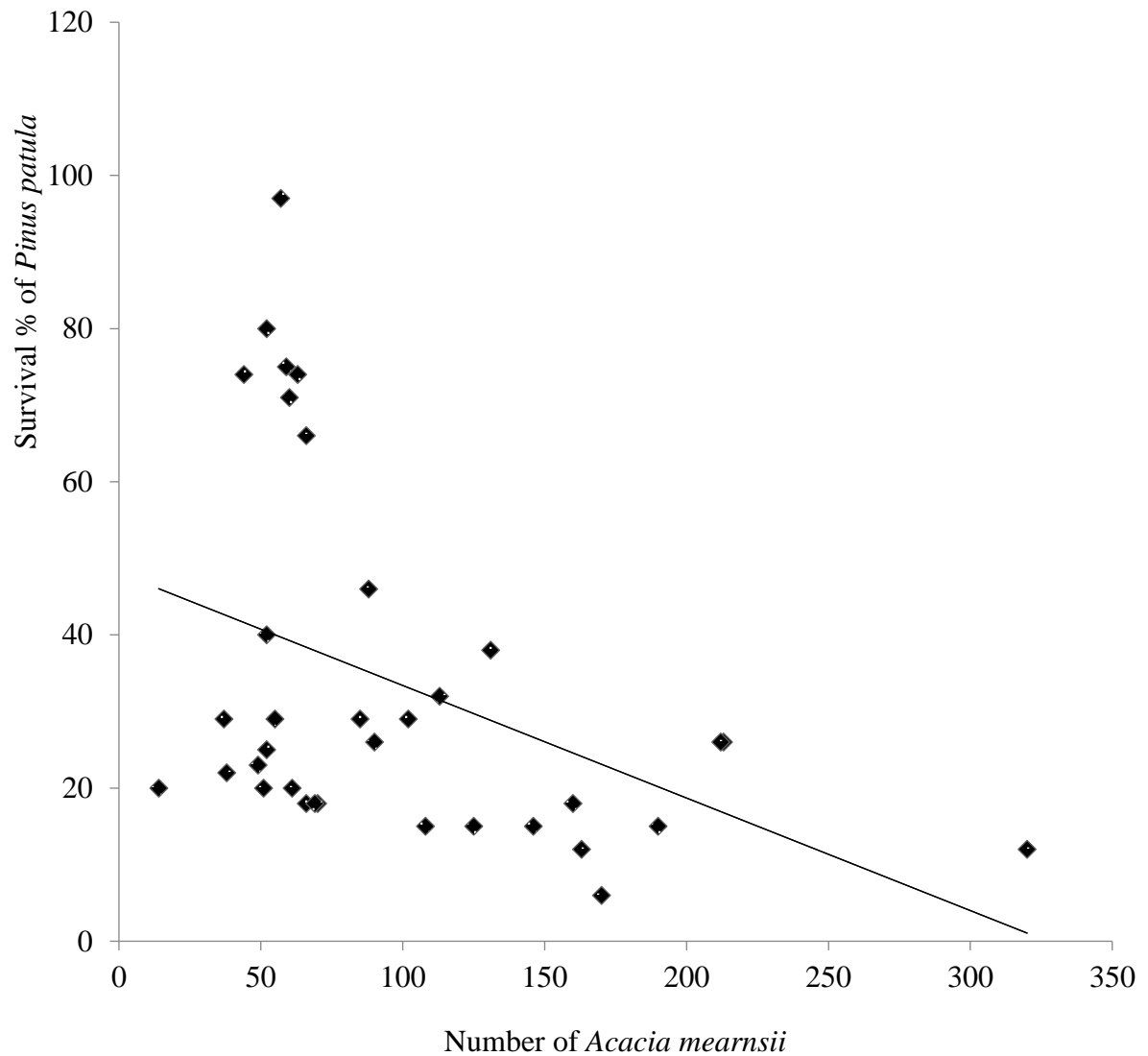


Figure 8: Relationship between *Pinus patula* survival and number of *Acacia mearnsii* in invaded areas

4.1.3 *Pinus patula* mean DBH at different concentration of *Acacia mearnsii* in invaded areas

The mean DBH of *Pinus patula* in relation to the concentration of *Acacia mearnsii* in different blocks is shown in (Fig. 8). There was a slight decrease of *P. patula* mean DBH as the number of *A. mearnsii* increased in almost all seven blocks surveyed with micro variation within blocks.

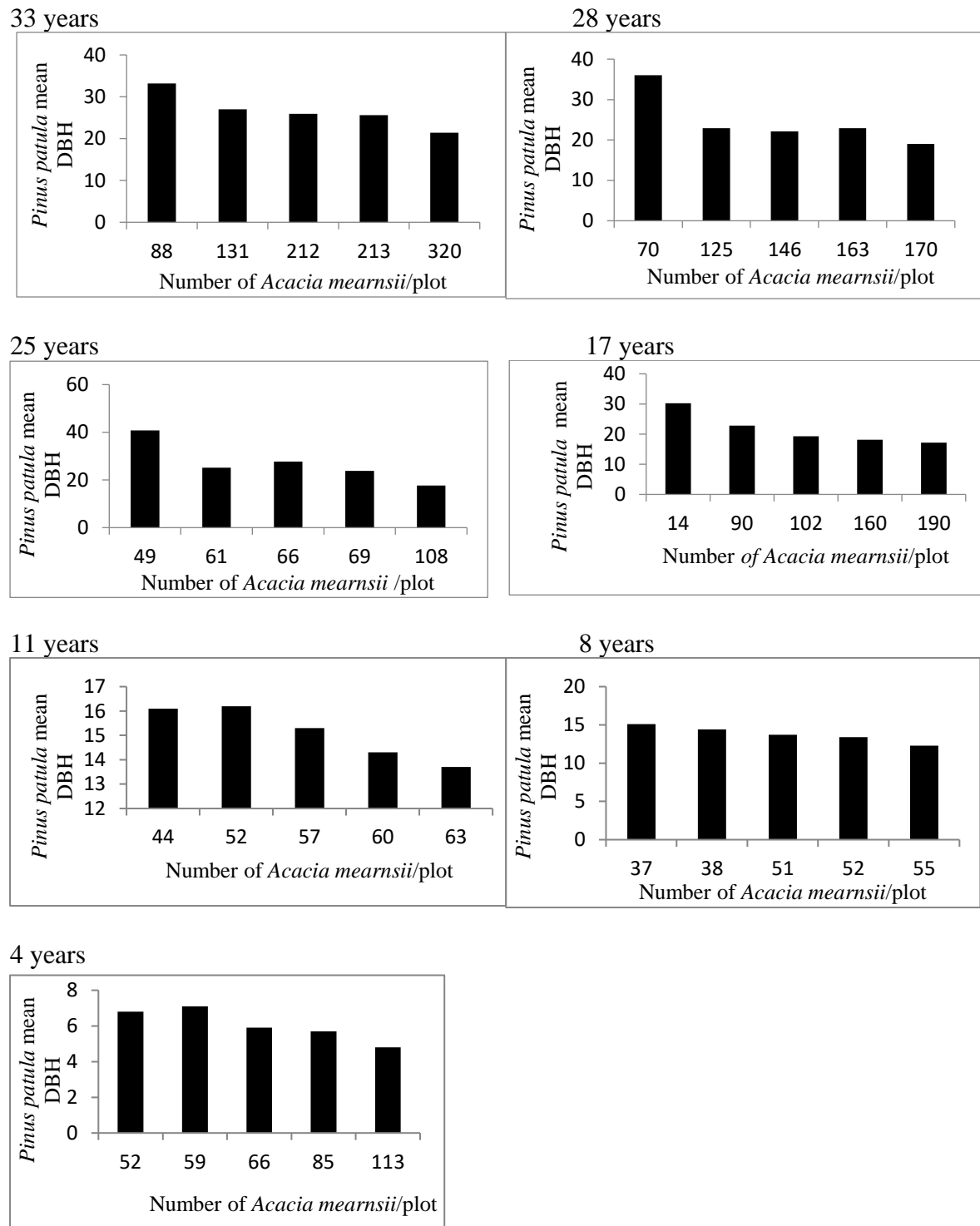


Figure 9: *Pinus patula* mean DBH at different concentration of *Acacia mearnsii* in plots across seven surveyed blocks

4.1.4 Density of *Pinus patula* in invaded and non-invaded areas

The number of *P. patula* stems was higher in non-invaded plots compared to invaded plots across all age classes. The overall mean density of *P. patula* ($SE \pm$) in invaded areas was 535(± 46), 793(± 25), 885 (± 23), 235(± 13), 203(± 7), 140(± 9) and 324(± 21) stems per ha while in non-invaded areas was 1044(± 39), 1057(± 23), 1121(± 27), 1038(± 32), 987(± 37), 840(± 19) and 770(± 17) stems per ha in 4, 8, 11, 17, 25, 28 and 33 years blocks respectively. The mean density of *P. patula* between invaded and non-invaded areas is shown in Fig. 9. The large difference of density was observed in mature *P. patula* blocks (17, 25, 28 and 33) compared to young blocks (4, 8 and 11). The overall results showed a significant difference in mean density of *P. patula* across all *P. patula* age class between invaded and non-invaded areas ($p < 0.005$).

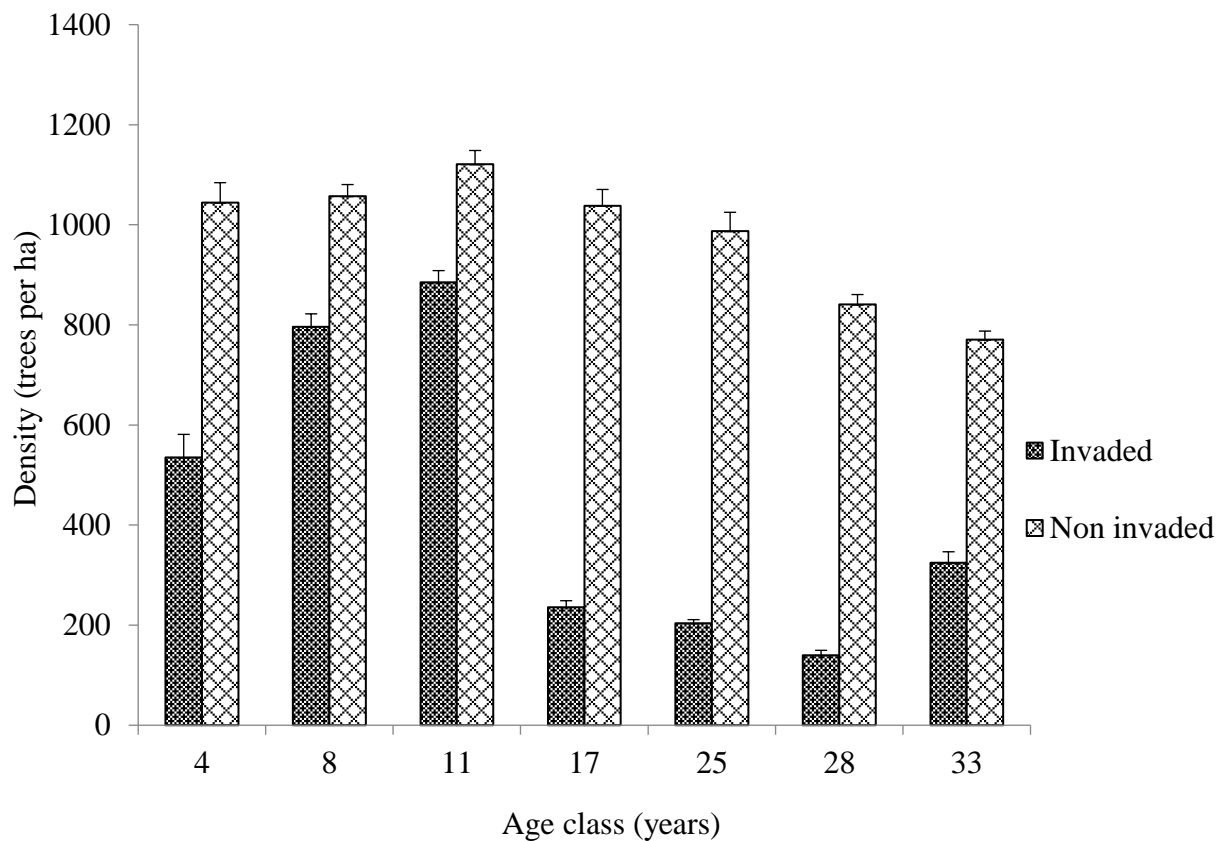


Figure 10: *Pinus patula* mean density ($SE \pm$) per hectare in invaded and non-invaded areas across seven surveyed blocks

4.1.5 Basal area of *Pinus patula* in invaded and non-invaded areas

Generally, *P. patula* basal area ($\text{m}^2 \text{ha}^{-1}$) differed significantly between invaded and non-invaded areas ($t = -3.238$, $df = 12$, $p = 0.0071$). Mean basal areas of *P. patula* in invaded and non-invaded areas were as shown in Table 3.

Table 3: Basal area of *Pinus patula* (Mean \pm SE) in invaded and non-invaded areas across seven age class

Age of <i>Pinus patula</i> (years)	<i>Pinus patula</i> Mean Basal area ($\text{m}^2 \text{ha}^{-1}$) in invaded areas	N	<i>Pinus patula</i> Mean Basal area ($\text{m}^2 \text{ha}^{-1}$) in non-invaded areas	N
4	1.6 ± 0.009	84	4.6 ± 0.07	174
8	12.2 ± 0.07	125	23.5 ± 0.29	181
11	16.5 ± 0.1	139	27.2 ± 0.29	196
17	10.0 ± 0.5	37	47.0 ± 0.7	190
25	15.3 ± 0.8	32	55.5 ± 1	169
28	14.0 ± 0.8	22	42.4 ± 1	132
33	16.1 ± 0.5	51	38.3 ± 1	121

4.1.6 Volume of *Pinus patula* in invaded and non-invaded areas

Volumetric yield analysis revealed that the overall volume of *P. patula* was higher in non-invaded areas compared to invaded areas across all ages (Fig. 10). Volume ($\text{m}^3 \text{ha}^{-1}$) in invaded areas was 8 (± 0.3), 132 (± 2.1), 199 (± 2.7), 152 (± 17.1), 223 (± 23.4), 204 (± 23.7) and 252 (± 14.5) while in non-invaded areas was 27 (± 0.4), 295 (± 3), 346 (± 3), 733 (± 8.6), 875 (± 11.8), 674 (± 13.1) and 605 (± 12.2) in 4, 8, 11, 17, 25, 28 and 33 years blocks respectively. It was also observed that volume in non-invaded areas increased as age increased up to 25 years which is the harvesting age then after decreased but in invaded areas volume was randomly distributed. There was a significant difference in volume per ha between invaded and non-invaded areas ($P < 0.05$).



Figure 11: *Pinus patula* mean volume (m³ ha⁻¹) (SE±) in invaded and non-invaded areas across seven surveyed blocks



Figure 12: Density of *Acacia mearnsii* in a newly planted *Pinus patula* block



Figure 13: *Pinus patula* block (17 years), “left” invaded side, “right” non-invaded side

4.2 Discussion

4.2.1 Distribution, density and structure of *Acacia mearnsii*

Results indicated that forest plantation block margins had the highest population density of *A. mearnsii* relative to within the plantation block areas. While there may have been management efforts at clearing stands of the *A. mearnsii* species in the SHFP area, the margins of the plantation blocks remained with higher colonization than inside the forest plantation. These findings corroborate with a study by Geldenhuys (1996), and Geldenhuys, Atsame-Edda and Mugure (2017), who found that the occurrence and abundance of most alien plants in the natural forest in South Africa were observed to be higher along the forest margins and in large gaps inside the forest than in other areas of the ecosystem. Several factors for this colonization around the margins may be considered including the role of light, openness, disturbances such as fire as well as high seed production and seed banks due to the long-term persistence of the established population of *A. mearnsii* (Geldenhuys, 1996). Zuengjuan, Chuanhong, Yongqi, Zhihe and Fuwen (2006) reported that *A. mearnsii* like other acacia is a shade-intolerant species hence cannot tolerate close and dense canopy inside the forest, it establishes well in disturbed areas. Hence, in facilitating the recovery of invaded areas, management efforts should target such areas to reduce the susceptibility of invasion in such commercial value plantations and other areas around the SHFP.

In the course of studying and understanding the invasive potential of two introduced tree species, *A. mearnsii*, and *Acacia dealbata*; Zuengjuan *et al.* (2006) indicated that the potential risk in the biological invasion of the two species is high in the subtropical environment such as

SHFP area. However, despite that environmental factors (e.g. climate, soils, aspect) influence occurrence and distribution of the species; life-history traits of the *A. mearnsii* and other woody species (e.g. age at reproductive maturity, seed dispersal mechanism, annual seed production, seed bank dynamics as well as seed germination and viability) have been found to strongly affect the germination, growth, survival and hence, invasiveness of the species (ZuengJuan *et al.*, 2006; Donaldson, Richardson & Wilson, 2014; Richardson & Kluge, 2008; Gioria, Pyšek & Moravcová, 2012; Geldenhuys *et al.*, 2017). Thus, in the course of addressing the invasion success and susceptibility of an ecosystem to invasion, the destruction of seed banks and thus the opportunities for intervention to reduce seed numbers for each of these life-history components would be the best management strategy. The reduction of seed banks is crucial for the overall success of the management initiatives against this species.

In the event of improving management actions through seed bank reduction, various approaches can be applied singly or in combination to further mitigate seed accumulation in the soil in invaded areas. This may include clearing of the *A. mearnsii* stands before they mature to flowering and thus limiting seed production as well as less intense fire application to reduce seed numbers in the leaf litter and upper seed bank. According to Holmes, Esler, Richardson and Witkowski (2008), clear-felling and removal of wood is the effective control method. Low intense fire is recommended since evidence has indicated a serious problem with high fire intensities in dense acacia stands (Richardson & Kluge, 2008).

Richardson and Kluge (2008) and Jimu and Ngoroyemoto (2011) reported that fire strongly stimulates *A. mearnsii* seed germination. We found that land preparation for tree planting in SHFP is mainly conducted by applying fire to burn debris after harvesting. This facilitates further *A. mearnsii* invasion in SHFP. Also, Katsvanga, Jimu, Zinner and Mupangwa (2009) reported that mammals and birds feed on *A. mearnsii* seed and hence facilitate its dispersal. It was found in this study that, birds, wild animals like Baboon as well as livestock were presence in the forest during a field survey. This poses the risk of further invasion as they influence the dispersion of *A. mearnsii* seed as well as the acid (heat in their stomach) stimulate the germination. Thus, in the event of controlling dispersal of *A. mearnsii* in SHFP, livestock grazing in the forest should be prohibited as well as bush animals and birds should be properly managed.

Furthermore, results showed seedlings being a dominant size class occupying the infested areas. The high density of seedlings confirms that *A. mearnsii* densification is taking place in the area. It also suggests a stable population of *A. mearnsii* with a high soil seed bank. This indicating a future burden to SHFP in managing it as well as threats to the performance of planted trees (especially pines) in terms of survival and growth if urgent actions will not be taken. This is because, *A. mearnsii* is more competitive due to the strong light demand and high growth rate (3 m per year) as compared to pines (mostly planted species in SHFP) which grows 2 m per year (Wiersum, 1991; Nigro, 2008). A study by Turvey, Attwill, Cameron and Smethurst (1984) that compared the performance of pine species in areas with different densities of acacia stems revealed that acacia stems at each density tested, competed and significantly reduced volume growth of pine trees (*P. radiata* and *P. elliotii*). Other documented effects *A. mearnsii* invasions include, reduce water yield and streamflow in catchment areas (Moyo *et al.*, 2009). The presence of *A. mearnsii* in SHFP pose the risk to the catchment forests and stream flows in and around the area. Catchment forests in SHFP drain its water in the Great Ruaha River which is very important for hydroelectric power, irrigation and wild animals in Ruaha national park.

Furthermore, it is still unclear if the current efforts to manage invasion inside blocks do this with a rather limited emphasis on managing the species on the edges of the blocks. If this is indeed the case, irrespective of the management effort to this, the regime approach of undermining eradication of the species on the edges of blocks may result in a significant loss of forestry resources, while it also exacerbates the invasion frequency and intensity in the area. This suggests that there may be significant forest loss occurring under such management approaches inside these areas despite any regulations, since their implementation under such approach may appear to be ineffective. From sustainable management of forestry resources, our results paint a bleak picture of the ability of *A. mearnsii* to penetrate and occupy a larger area of forest plantations unintentionally. To effectively control the invasion and hence, reduce management cost in the plantation forests, the management authorities need to prioritize on the approaches of dealing with a seed bank and stands in the manner indicated above.

4.2.2 Survival, density and volume of *Pinus patula* between invaded and non-invaded areas

Results from this study indicated a negative (competitive) species interaction which occurs when one species exerts a negative effect on the other species due to the competition for resources such as light, nutrients, and moisture (Vandermeer, 1989). Competition from *A. mearnsii* in this study significantly reduced the survival and growth of *P. patula*. *Acacia mearnsii* is known to be more competitive and high light requiring species as it grows faster (3 m per year) as compared to *P. patula* (2 m per year) and thus competing with other species for light and other resources. (Wiersum, 1991; Nigro, 2008). Relationship between the survival of *P. patula* and density of *A. mearnsii* in Fig. 8 and lower density of *P. patula* in invaded than non-invaded areas in Fig. 10 demonstrate the capacity of *A. mearnsii* to outcompete *P. patula* effectively. These results are in line with the mortality model developed by Malimbwi *et al.* (2016) which states that tree mortality is mainly caused by competition for resources such as light, moisture and nutrients and when it sets in, the small and weak trees die progressively with increasing age.

Significantly lower *P. patula* basal area and volume in invaded as compared to non-invaded areas (Table 3 and Fig. 11) as well as a decrease in mean *P. patula* DBH in Fig. 9 also suggests an increase in resource competition between the two species. The difference in basal area and volume between invaded and non-invaded areas in this study was associated with fewer and weak *P. patula* stems in invaded areas as compared to non-invaded areas. A study by Forrester, Bauhus, Cowie, Mitchell and Brockwell (2007) that compared the performance of *P. radiata* in monoculture and when mixed with nitrogen-fixing species *A. mearnsii* found that, *P. radiata* diameter and height which reflect the volume and basal area of a tree were smaller in the mixture than in monoculture. Moreover, a study by Turvey *et al.* (1984) that compared the performance of pine species in areas with different densities of naturally regenerated acacia stems including *A. mearnsii* revealed that acacia stems at each density tested, competed and significantly reduced volume growth of pine trees (*P. radiata* and *P. elliottii*). Forester *et al.* (2007) and Turvey *et al.* (1984) concluded that despite acacia species such as *A. mearnsii* being good in Nitrogen (N) fixation, competition for resources other than N such as light, soil moisture, and other nutrients appeared to outweigh any positive effect that might have occurred through increased N availability.

The volume, which is the measure of forest productivity determines the economic value of the forest (Skovsgaard & Vanclay, 2008). This study reports significant productivity loss caused by the *A. mearnsii* invasion, which needs urgent management actions. The need for urgent management action is due to the potential of SHFP to the economy of the country especially in supplying wood materials to the industries, employment creation and reducing pressure to natural forests (Ngaga, 2011). Natural forests in Tanzania and globally continue to face various threats and disturbances such as fire, illegal harvesting and extraction, unsustainable land-use conversions (Bebi *et al.*, 2017; Blake *et al.*, 2018) and invasive species (Donaldson *et al.*, 2014) which significant trends in forests and forestry loss over time. This can have potentially irreversible economic and ecological consequences (Balmford *et al.*, 2002; Foley *et al.*, 2005), and limits the possibility of Tanzania achieving most of the sustainable development goals (including industrial and economic growth) whose targets are set before 2030. Therefore, anything that threatens the sustainability of SHFP should be managed urgently by considering its importance to society and biodiversity as a whole.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study has shown that *A. mearnsii* stems density was high in blocks margin and open areas as compared to inside blocks. Also, it shows that *A. mearnsii* has a negative influence on the survival and growth of *P. patula*. It appears from the blocks examined that a relatively low density of acacia stems in a pine stand adversely reduce pine growth. Certainly, it is clear that in areas dominated by *A. mearnsii*, the performance of *P. patula* was lower than in areas with no acacia stands. *Acacia mearnsii* population density was significantly higher in plots that were located along blocks margins than those that were located inside blocks. Although coverage for seedlings, saplings, sub-adults, and adults varied between plots located along margins and inside the blocks, this variation did not differ significantly, suggesting similar recruitment between these locations. This study has provided valuable information for future population monitoring and suggests that management actions for controlling the invasion and mitigating the further spread of this invasive species are a matter of urgency.

5.2 Recommendations

These findings should alert the management of SHFP and the government on the rapid occupation and consequence of the invasive tree *A. mearnsii* on the productivity of wood tree *P. patula*. The findings here provide stark evidence of the pressing need for coordinated specific and integrated management actions that can address the problem. To realize the sustainable production and efficient turnover from the SHFP, the study propose a systematic, consistent proactive approach to manage the invasion based on their extent of infestation in different areas of the plantation forest. Also integrating invasive species management actions across the entire supply chains (harvesting regimes) of forestry resources should be adopted to prevent further invasion in SHFP and elsewhere.

In the course of addressing the invasion success and susceptibility of an ecosystem to invasion, the destruction of seed banks to reduce seed numbers could be the best management strategy. The reduction of seed banks is crucial for the overall success of the management initiatives against this species. In the event of improving management actions through seed bank

reduction, various approaches can be applied singly or in combination to further mitigate seed accumulation in the soil in invaded areas. This may include clearing of the *A. mearnsii* stands before they mature to flowering and thus, limiting seed production, less intense fire application to reduce seed numbers in the leaf litter and upper seed bank. Other controlling options could be by regulating the dispersal mechanisms of the species.

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RESEARCH OUTPUTS

Output 1: Paper accepted for publication

Research Manuscript Titled “Performance of *Pinus patula* in Areas Invaded by *Acacia mearnsii* in Sao Hill Forest Plantation, Southern Tanzania”. Accepted for publication in the **Journal of Sustainable Forest under Tylor and Francis**

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11-Mar-2020

Dear Ms Kingazi:

Your manuscript entitled "Performance of *Pinus patula* in Areas Invaded by *Acacia mearnsii* in Sao Hill Forest Plantation, Southern Tanzania", which you submitted to Journal of Sustainable Forestry, has been internally reviewed. The external reviewer could not trace the corrections to the manuscript due to the auto numbering inserted when ScholarOne system generates the pdf. However, we have checked your manuscript and request that the authors conduct a final check and submit a cleaned version that is ready for publication. The comments that should be reconsidered are included at the bottom of this letter.

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Performance of *Pinus patula* in Areas Invaded by *Acacia mearnsii* in Sao Hill Forest Plantation, Southern Tanzania

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Abstract

Problems associated with the invasiveness of exotic tree species have increased recently causing vast damage in ecology and economy. Sao Hill Forest Plantation (SHFP) is under the *Acacia mearnsii* invasion which threatens the productivity of the planted species. This study compared the performance of *Pinus patula* in areas invaded by *A. mearnsii* with non-invaded areas in SHFP. Purposive and systematic random sampling was used to select sample plantation blocks and plots allocation, respectively. Data collected included the number of stems, height and diameter for *P. patula* and only stem counts for *A. mearnsii*. Results showed that the survival of *P. patula* was decreasing as the density of *A. mearnsii* increased ($r = -0.36$, $p = 0.033$). Also, there was a significant difference between invaded and non-invaded areas in both, density, basal area and volume of *P. patula* ($t = -4.35$, $p = 0.0009$), ($t = -3.238$, $p = 0.0071$) and ($t = -2.937$, $p = 0.0124$) respectively with higher performance being in non-invaded areas. Results suggest that *A. mearnsii* has a negative influence on the survival and growth of *P. patula*. We recommend that forest management should incorporate invasive control measures given that tree invasions can influence the performance of desirable tree species.

Keywords: *Acacia mearnsii*, *Pinus patula*, performance, invaded and non-invaded, competition, invasive alien tree.

Introduction

Biological invasions have increased rapidly all over the world in recent decades (Van Wilgen et al., 2011). It is one of the significant threats to biodiversity, economy, and environment by causing vast damage to valuable ecosystems and their services (Simberloff, 2013). Biological invasions associated with non-native trees have increased in many parts of the world (Richardson et al., 2014). These invasions cause a detrimental impact on the environment, society, and economic activities and are the key drivers of global change (Shackleton, Maitre, Pasiecznik, & Richardson, 2014). Invasive tree species are known to reduce native wood species density, growth and richness (Shackleton, Le, Wilgen, & Richardson, 2015; Van Der Waal, 2009). Likewise, such invasive trees negatively affect ecosystem services such as water supply, reduces grazing land, affects soil quality as well as reducing crop production (Shackleton et al., 2014; Reda & Tewelde, 2017). Australian acacias (genus *Acacia*) are a useful model group for understanding tree invasions (Richardson et al., 2011)

Acacia mearnsii is among the Australian tree species that were introduced to new locations worldwide (e.g. Tanzania) for different purposes such as wood and tannin extraction (Richardson, Roux, & Wilson, 2015; Richardson et al., 2011), and later became an invasive alien species (Rejm & Richardson, 2013). Invasiveness of *A. mearnsii* is due to its ability to produce large numbers of long-lived seeds, rapid stem growth, allelopathic effect and development of a dense crown that hinders other vegetation from growing (Global Invasive Species Database, 2015). *Acacia mearnsii* is among the 100 worst invaders in the world (Global Invasive Species Database, 2015). In Africa, particularly South Africa, *Acacia mearnsii* is considered a major invasive tree species covering about 2.5 million hectares of land in forest, riparian and rangeland areas (Moyo & Fantubi, 2010). *Acacia mearnsii* has a variety of negative impact such as altering stream functionality and reducing species diversity of aquatic biota (Van Der Waal, 2009; Railoun, 2018), affecting soil and litter carbon stock (Oelofse & Jakob, 2015). Also, it alters soil physiochemical properties and changes microbial function and structure as well as competing and replacing native vegetation (Souza-alonso, 2017).

However, apart from being a threat to native vegetation, *A. mearnsii* can also invade or naturally regenerate in exotic vegetation (Geldenhuys, 1986; Turvey, Attwill, Cameron, & Smethurst, 1984). The competitive interaction between acacias and some forest plantation species has previously been documented elsewhere (Turvey et al., 1984; Forrester, Bauhus,

Cowie, Mitchell, & Brockwell, 2007). Turvey et al. (1984) for-instance, studied the effect of naturally regenerated acacias on the growth of *Pinus radiata* and *Pinus elliottii* and found that, *A. mearnsii* depressed volume growth of the two species. A study about competitive interaction between *A. mearnsii* and *Pinus radiata* by Forrester et al. (2007) revealed that competition from *A. mearnsii* reduced *P. radiata* height and diameter growth.

In Tanzania, *A. mearnsii* is one of the significant invasive species, which affects both natural and plantation forests (Richard, 2020). The study conducted by Richard (2016) reported the invasion of *A. mearnsii* in Chome Nature Reserve, Tanzania, whereby the species reduced the regeneration of native species and water yield of the forest. Nagabona & Chitiki (2016) reported that SHFP is under the *A. mearnsii* invasion which threatens its productivity by increasing operational cost (uprooting cost). The control method (uprooting) has not worked as the *A. mearnsii* is still spreading and growing (Nagabona and Chitiki, 2016). Moreover, Nagabona and Chitiki (2016) further reported that there is a growing concern over the increase of *A. mearnsii* in this plantation, where planted trees are being suppressed and sometimes killed eventually reducing stocking of the planted trees at the end of the rotation

Therefore, this study aimed at determining the influence of *A. mearnsii* on the survival and growth of *P. patula* (the main species planted in this plantation and surrounding areas) by comparing its performance between invaded and non-invaded areas. Generally, the knowledge about the invasion of alien woody species to another alien tree species in forest plantation and their associated effects is inadequate with a limited literature, especially in East Africa. Thus, this study will add general knowledge about the effect when alien tree species invade another alien tree species in the forest plantation and its associated effect on productivity. Also, findings from this study will provide baseline information and a comprehensive understanding of the implications of *A. mearnsii* invasion on the management and productivity of *P. patula* in SHFP and the surrounding areas. This information will be incorporated into management actions towards curbing the problem and its consequences on biodiversity loss and to ecosystem services provisioning including timber production in the plantation and surrounding areas.

Materials and Methods

Study site

This study was conducted in SHFP which is located in the Southern Highlands of Tanzania, Iringa region, Mufindi District at (8°18'S to 8°33'S and 35°6'E to 35°20'E) with the altitude which ranges from 1700 m to 2000 m.a.s.l (Petro, 2011). The area is a rolling plateau with low hills and wide, flat-bottomed valleys (Silayo, Kiparu, Mauya, & Shemwetta, 2010). The area receives between 750 and 2010mm of rainfall annually. The rainfall pattern is unimodal with a single rain season from November through May and a dry season during the rest period of the year (Ngaga, 2011). Temperatures are relatively cold, reaching close to a freezing point between June and August. The mean monthly minimum and maximum temperatures are 10°C and 20°C, respectively (Petro, 2011). Soils are mainly dystic nitosols in association with orthic acrisols and are relatively homogeneous in the entire area, the soil colour ranging from very dark brown to yellow-orange (Ngegba, Mugasha, & Chamshama, 2001).

Sao Hill Forest Plantation was established in 1939 with the primary objective of supplying raw materials to wood industries (pulpwood and timber), protecting water catchment areas, preventing soil erosion, improving local climate, and acting as a buffer between local people and the natural forest (Ngaga, 2011). The plantation covers a total area of 135,903 ha out of which, planted area is 57, 570 ha. The timber species planted in SHFP include *Pinus patula*, *Pinus elliottii*, *Pinus caribea*, *Pinus cassia*, *Eucalyptus saligna*, *Eucalyptus maidenii*, *Eucalyptus grandis* and *Cupressus lusitanica*. The remaining area is composed of natural forests, and river valleys managed as water catchment, extension and residential areas (Tanzania Forest Services agency, 2020). Sao Hill Forest Plantation harvests about 600,000 m³ of wood raw materials per year, where 80% comes from *P. patula*. The price per cubic meter of standing volume is about 12 USD (Y. Salum, forest manager, personal communication, March 29, 2019). This plantation remains to be a significant source of wood, apart from employing locals (Ngaga, 2011). It supplies about 85% of the raw materials used by wood industries in Tanzania. The production of timber, fibre and fuelwood has significantly reduced pressure on natural forests in the Southern Highlands of Tanzania (Ngaga, 2011).

Sampling design

A reconnaissance survey was conducted between December 2018 and January 2019 using forest road transect and transect walk in off-road areas to determine sampling strategy. Data collection was done in March 2019.

Seven plantation blocks of *P. patula* were purposively selected for data collection. Plantation block as per this study refers to a unit of forest plantation with relatively similar growing conditions and tree species of the same age. Before selection, blocks were grouped into the following age classes 1-5 years, 6-10 years, 11-15 years, 16-20 years, 21-25 years, 26-30 years and 31-35 years (Vesa et al., 2010). In each age class, *P. patula* blocks with the following ages 4, 8, 11, 17, 25, 28 and 33 respectively were selected to represent others. The choice of the sample *P. patula* block was based on the dominance of *A. mearnsii* with at least one non-invaded side for comparison. In each sample block, about ten circular plots of 10m radius (Vries, 1996) were systematically randomly established along invaded and non-invaded side (5 plot each side). The distance between plots in both invaded and the non-invaded side was at least 25m to ensure plots variation (Ward & Sutherland, 2006). Circular plots were adopted following Vesa et al. (2010) whose study revealed that, the use of circular plots in forest inventory increase the accuracy of the measurement, sampling intensity of large trees, and simultaneously saves time. The total number of plots was 70 (being 35 in the invaded areas and 35 in the non-invaded areas).

Data collection

In each plot, diameters at breast height (DBH) over bark and total tree heights of *P. patula* were measured in both invaded and non-invaded areas using a caliper and digital hypsometer (vertex) respectively. The diameter was measured for all trees in the plots while the height was measured for a subset of trees and the allometric equation was used to estimate the height of the remained trees (Vesa et al., 2010). Stem counts of both *P. patula* and *A. mearnsii* were also recorded. The following equation developed by (Malimbwi, Mugasha, & Mauya, 2016) was used to estimate the height (m);

$$Height = 1.3 + (dbh^2 / 13.63898 + 0.026482 \times dbh^2) \quad (1)$$

where dbh is the diameter at breast height (cm).

Data analysis.

Data analysis was done on survival, density, basal area and volume of *P. patula* and only density for *A. mearnsii*. Survival was calculated based on the planting space of *P. patula*, which is 3m × 3m as per the Tanzania forest plantation guideline (URT, 2017). Stem density (ha⁻¹) of

both *A. mearnsii* and *P. patula* was calculated by simply dividing stem counts in a plot by plot area. The standing volume ($\text{m}^3 \text{ha}^{-1}$) of *P. patula* was computed using equation (2) (Malimbwi et al., 2016).

$$\text{Volume} = \exp (-9.04925 + 1.14781 \times \ln(\text{height}) + 1.5496 \times \ln(\text{dbh})) \quad (2)$$

After calculations, summaries of results for the mean; density (ha^{-1}), basal area ($\text{m}^2 \text{ha}^{-1}$) and volume ($\text{m}^3 \text{ha}^{-1}$) of *P. patula* in both invaded and non-invaded plots were subjected to paired sample T-test (two tails) for the statistical test in R software version 3.5.2. The relationship between the density of *A. mearnsii* and survival of *P. patula* was analyzed by Pearson's correlation analysis.

Results

Relationship between the survival of Pinus patula and the density of Acacia mearnsii across seven age classes

The survival of *P. patula* in non-invaded areas in both 4, 8, 11, and 17 years blocks was 100% while in invaded areas survival was 47%, 73%, 79%, and 20% respectively. Also, the survival of *P. patula* in the block of 25, 28, and 33 years was 17%, 11%, and 29% in invaded areas while in non-invaded areas was 97%, 76%, and 70% respectively. Generally, there was a significant negative correlation between *P. patula* survival and density of *A. mearnsii* ($r = -0.36$, $df = 34$, $p = 0.033$; Figure 1).

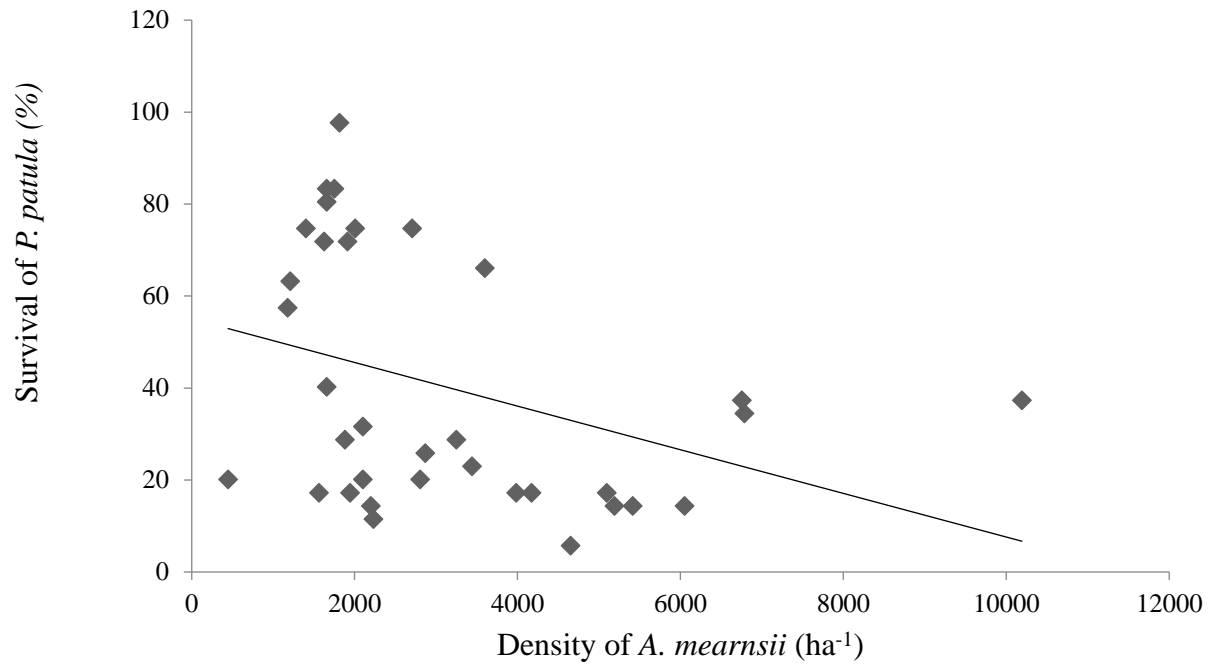


Figure 1: Relationship between survival of *P. patula* and the density of *A. mearnsii* across seven age classes ($r = -0.36$, $df = 34$, $p = 0.033$).

Density of *Pinus patula* in Invaded and non-invaded areas

Stem density of *P. patula* in invaded areas was significantly lower than that in non-invaded areas across all age classes ($t = -4.35$, $df = 12$, $p = 0.0009$). The mean densities of *P. patula* between invaded and non-invaded areas were as shown in Table 1. A large difference of *P. patula* density between invaded and non-invaded areas was observed in mature *P. patula* blocks (aged 17, 25, 28 and 33) as compared to blocks with young *P. patula* (aged 4, 8, and 11; Table 1).

Table 1: Stem density (\pm S.E) of *P. patula* in invaded and non-invaded areas across seven age class

Block No	Age	<i>Pinus patula</i> Mean		<i>Pinus patula</i> Mean	
		Density	/ha	Density	/ha Non-
		Invaded	N	Invaded	N
1	4	535 \pm 46	84	1044 \pm 39	174

2	8	796 ± 25	125	1057 ± 23	181
3	11	885 ± 23	139	1121 ± 27	196
4	17	235 ± 13	37	1038 ± 32	190
5	25	203 ± 7	32	987 ± 32	169
6	28	140 ± 9	22	840 ± 19	132
7	33	324 ± 21	51	770 ± 17	121

Basal area of Pinus patula in invaded and non-invaded areas

Generally, *P. patula* basal area ($\text{m}^2 \text{ha}^{-1}$) differed significantly between invaded and non-invaded areas ($t = -3.238$, $df = 12$, $p = 0.0071$). Mean basal areas of *P. patula* in invaded and non-invaded areas were as shown in Table 2.

Table 2: Basal area of *P. patula* (Mean ± SE) in invaded and non-invaded areas across seven age class

Age of <i>Pinus patula</i>	<i>Pinus patula</i> Mean Basal area ($\text{m}^2 \text{ha}^{-1}$) in		<i>Pinus patula</i> Mean Basal area ($\text{m}^2 \text{ha}^{-1}$) in	
	invaded areas	N	non-invaded areas	N
4	1.6 ± 0.009	84	4.6 ± 0.07	174
8	12.2 ± 0.07	125	23.5 ± 0.29	181
11	16.5 ± 0.1	139	27.2 ± 0.29	196
17	10.0 ± 0.5	37	47.0 ± 0.7	190
25	15.3 ± 0.8	32	55.5 ± 1	169
28	14.0 ± 0.8	22	42.4 ± 1	132
33	16.1 ± 0.5	51	38.3 ± 1	121

Volume of Pinus patula in invaded and non-invaded areas

The standing volume of *P. patula* was significantly different ($t = -2.937$, $df = 12$, $p = 0.0124$) between invaded and non-invaded areas. A large volume was recorded in non-invaded areas as compared to invaded areas across all selected blocks. While volume in non-invaded areas increased as age increased up to 25 years, no trend was observed in invaded areas. Mean

volumes ($\text{m}^3 \text{ha}^{-1}$) of *P. patula* in invaded, and non-invaded areas were as represented in Table 3.

Table 3: *Pinus patula* mean volume (Mean \pm SE) in invaded areas and non-invaded areas

Age of <i>Pinus patula</i> block	<i>Pinus patula</i> Mean Volume ($\text{m}^3 \text{ha}^{-1}$) in invaded areas	N	<i>Pinus patula</i> Mean Volume ($\text{m}^3 \text{ha}^{-1}$) in non-invaded areas	N
4	8 ± 0.3	84	27 ± 0.4	174
8	132 ± 2.1	125	295 ± 3	181
11	199 ± 2.7	139	346 ± 3	196
17	152 ± 17.1	37	733 ± 8.6	190
25	223 ± 23.4	32	875 ± 11.8	169
28	204 ± 23.7	22	674 ± 13.1	132
33	252 ± 14.5	51	605 ± 12.2	121

Density of Acacia mearnsii in each surveyed block

The density of *A. mearnsii* in each surveyed block was as indicated in Table 4. The highest density of *A. mearnsii* was recorded in the 33 and 28 years old *P. patula* blocks. In all blocks, *A. mearnsii* seedlings appeared to be the dominant population followed by sapling, pole, and adults. There were no mature *Acacia mearnsii* in 4, 8 and 11 years blocks but were found only in 17, 25, 28 and 33 years blocks.

Table 4: Mean density (ha^{-1}) of *A. mearnsii* (Mean \pm SE) in invaded areas

Age of <i>Pinus patula</i> Block	Seedlings	Saplings	Poles	Adults	N
4	1280 ± 67	891 ± 55	216 ± 38	0	964
8	757 ± 26	535 ± 29	191 ± 16	0	674
11	719 ± 30	611 ± 21	426 ± 12	0	353
17	1242 ± 218	923 ± 188	1095 ± 126	280 ± 23	556
25	503 ± 64	414 ± 57	1063 ± 48	267 ± 13	276
28	1993 ± 203	1171 ± 91	968 ± 70	159 ± 14	233
35	2917 ± 191	2242 ± 263	910 ± 87	70 ± 13	262

NB: N = Total number of *A. mearnsii* stems counted in plots in each block

Discussion

Results from this study indicated a negative (competitive) species interaction which occurs when one species exerts a negative effect on the other species due to the competition for resources such as light, nutrients, and moisture (Vandermeer, 1989). Competition from *A. mearnsii* in this study may have significantly reduced the survival and growth of *P. patula*. *Acacia mearnsii* is known to be more competitive and high light requiring species as it grows faster (3 m per year) as compared to *P. patula* (2 m per year) and thus competing with other species for light and other resources. (Wiersum, 1991; Nigro, 2008). The regression relationship between survival of *P. patula* and density of *A. mearnsii* in Figure 1 and lower density of *P. patula* in invaded than non-invaded areas in Figure 2 demonstrate the capacity of *A. mearnsii* to outcompete *P. patula* effectively. These results are in line with the mortality model developed by Malimbwi et al. (2016) which states that, tree mortality is mainly caused by competition for resources such as light, moisture and nutrients and when it sets in, the small and weak trees die progressively with increasing age.

Significantly lower *P. patula* basal area and volume in invaded as compared to non-invaded areas (Table 2 and 3) also suggests an increase in resource competition between the two species. The difference in basal area and volume between invaded and non-invaded areas in this study was associated with fewer and weak *P. patula* stems in invaded areas as compared to non-invaded areas. A study by Forrester *et al.* (2007) compared the performance of *P. radiata* in monoculture and when mixed with nitrogen-fixing species *A. mearnsii* found that, *P. radiata* diameter and height which reflect the volume and basal area of a tree were smaller in the mixture than in monoculture. Moreover, a study by Turvey *et al.* (1984) that compared the performance of pine species in areas with different densities of naturally regenerated acacia stems (including *A. mearnsii*) revealed that acacia stems at each density tested, competed and significantly reduced volume growth of pine trees (*P. radiata* and *P. elliottii*). Forrester *et al.* (2007) and Turvey *et al.* (1984) concluded that despite acacia species such as *A. mearnsii* being good in Nitrogen (N) fixation, competition for resources other than N such as light, soil moisture, and other nutrients appeared to outweigh any positive effect that might have occurred through increased N availability.

The volume, which is the measure of forest productivity determines the economic value of the forest (Skovsgaard & Vanclay, 2008). This study reports significant productivity loss caused by the *A. mearnsii* invasion, which needs urgent management actions. Urgent management action is needed since *A. mearnsii* density in all surveyed blocks was high with seedlings and saplings being the dominant age classes in the population (Table 4). In most cases, *A. mearnsii* stems were observed in the planted trees along or near the margin of the plantation block. Our findings corroborate with a study by Geldenhuys (1996) and Geldenhuys et al. (2017), who found that the occurrence and abundance of most alien plants in the natural forest in South Africa were observed to be higher along the forest margins and in large gaps inside the forest than in other areas of the ecosystem. The high number of seedlings and saplings suggests a stable population with high seed bank in the soil; this indicates a future burden to SHFP management if urgent actions will not be taken. Thus, in the course of addressing the invasion success and susceptibility to further invasion, the destruction of seed banks to reduce seed numbers in the soil as well as clearing *A. mearnsii* stands before they mature to flowering would be the best management strategy.

In conclusion, the difference in performance between invaded and non-invaded areas observed in all surveyed blocks and results from similar studies gives evidence that *A. mearnsii* has an influence (reduce) on *P. patula* survival and growth. These findings should alert the management of SHFP and the government on the consequence of the invasive tree *A. mearnsii* on the productivity of wood tree *P. patula*. Furthermore, observation from this study provides stark evidence of the pressing need for coordinated, specific and integrated management actions that can address this problem to realize the sustainable production and efficient turnover from the plantation. We propose a systematic and consistent proactive approach to managing the invasion based on their extent in different areas of the plantation forest. However, this study did not incorporate environmental factors such as the difference in soil nutrients and moisture in comparing *P. patula* performance between invaded and non-invaded areas. Therefore, we recommend further studies to be conducted on the impact of acacia invasion on the survival and growth of other species which will incorporate environmental variability as a factor of change or difference between invaded and non-invaded areas.

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Declaration of interest statement

The authors declare that there are no competing interests while submitting the manuscript for publication.

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